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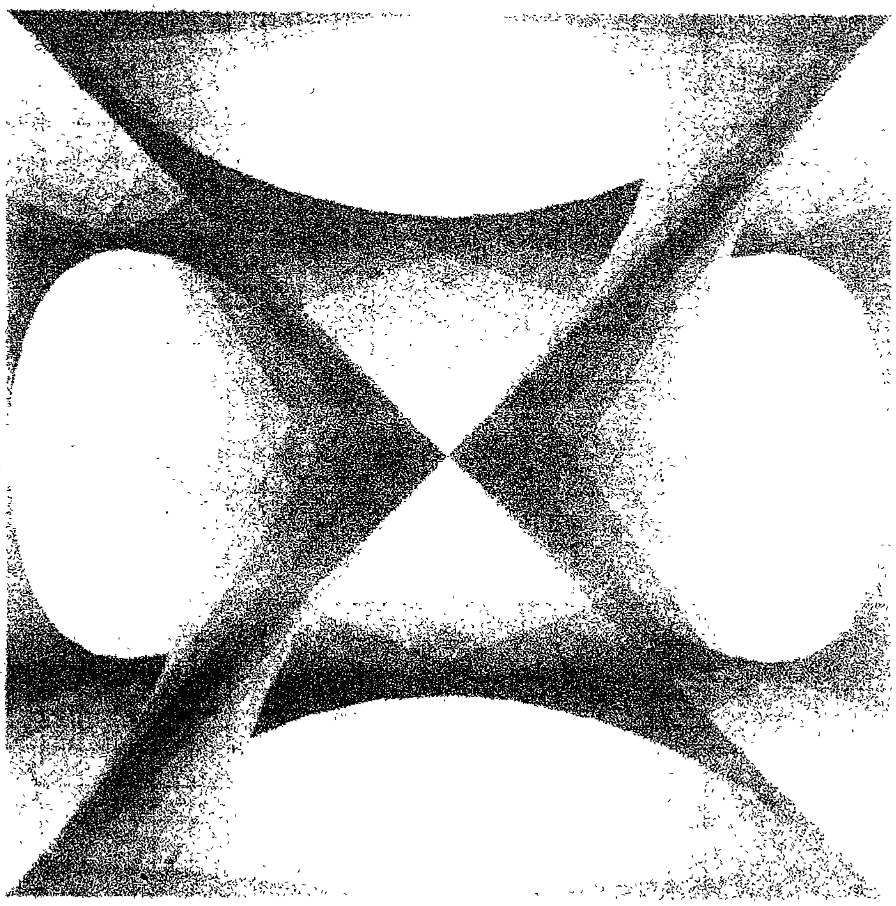

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SYMMETROSPECTIVE: A HISTORIC VIEW

THE BIRTH OF THE TUNNEL DIODE, AND THE SEMICONDUCTOR SUPERLATTICE

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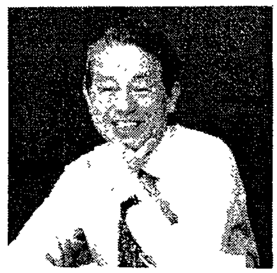

Abstract: *The paper gives an insight in the history of two discoveries by the author. Having looked back to the birth of the* tunnel diode, *the reader is made acquainted with an effect born with an idea of a special periodicity (translational symmetry) property, namely the* semiconductor superlattice, *and how did it lead to physical applications. Finally lessons are summarized.*

DYNAMIC EVOLUTION IN SCIENCE AND TECHNOLOGY: THE BIRTH OF THE TUNNEL DIODE

Recently, a friend of mine showed me a proceeding of a meeting held in Osaka, Japan some forty-one years ago. Apparently, at that meeting, I gave a talk on the subject of transistors. The year was 1953, and I was not yet thirty years of age. According to the proceeding I began my speech with the following words:

"Since the beginning of this century, there has been great progress made in telecommunications thanks to the tremendous advances in the vacuum tube. However, we appear to be approaching the limits of progress in vacuum tube design and production. Now that we have reached this stage, it can be said, quite ironically, that the vacuum tube itself has become the greatest obstacle to the next stage of dramatic progress in the field of telecommunications.

I would like to talk a little today about semiconductor amplifiers, which made their appearance with the promise to overcome the limitations of the vacuum tube. As you know, these semiconductor amplifiers came to be known as transistors.

We first became aware of the transistor in 1948. Our source of information was a paper jointly written by John Bardeen and Walter Brattain of Bell Telephone Laboratories, which appeared in Physical Review, an American journal of physics. The term 'transistor' was used for the first time in the title of that paper and was described as a semiconductor triode."

As an aside, let me read you the words which appear below the bust of Alexander Graham Bell, the inventor of the telephone, which stands in the foyer of the main entrance to Bell Laboratories. "Leave the beaten track occasionally and dive into the woods. You will be certain to find something that you have never seen before." I suppose that a number of great inventions and discoveries have been made by searching in the woods. The transistor was one such case. The inventors, the aforementioned Bardeen and Brattain, were awarded the Nobel Prize in 1956 along with William Shockley for this, the most remarkable invention of the twentieth century.

It was in 1947 that I finished my studies at the Physics Department of Tokyo University and moved on to life as a researcher. My area of research was vacuum tube materials, and I was employed by Kobe Industries, a company, which no longer exists today. Coincidentally, that was the same year the transistor was invented. Looking back on history, the decade of the 1950s was quite remarkable. It was a period of technological innovation in the field of electronics: The epoch-making evolution from vacuum tubes to transistors led to a vast improvement in the performance of all electronic products, including consumer-oriented goods, telecommunications and data processing. It is no exaggeration to say that today's information oriented society was made possible by this technological innovation. Japanese electronics industries played an important role in this evolution and thus made a significant contribution to the economic growth in this country.

I feel extremely fortunate to have started my career in the midst of such a period of technological innovation. This environment stimulated me, encouraged me, and led me to the work for which I would later be awarded the Nobel Prize. This example of technological transformation stands as an important lesson for us. The transistor is substantially different from the vacuum tube, and no amount of research and improvement of the vacuum tube could have led to the birth of the transistor. There is a tendency, especially in the stable societies, to assume that the future is simply a natural extension of the past and the present. However, during periods of great change, innovations are born which have never existed before, and it is actually these innovations which shape and form the future. Needless to say, it is the power of creativity, which plays the decisive role in this process.

The powers of the human mind can be divided into two major categories. One is *the power of judicial mind*, which allows human beings to understand fundamental principles and to make discretionary judgements. The other is *the power of the creative mind*. The former acts as our tool in analyzing, understanding, selecting, and making fair judgements. The latter involves the ability to create new ideas through perceptiveness and the creative process. It is this creativity which provides the engine for progress and which has sustained the advance of human civilization.

Of course, it is through the mutual interaction of these two powers that a far greater power is generated. If we say that creativity is individualistic and represents the challenge of the future, then the power of discretion can be said to have a non-individualistic aspect and can be essentially concerned with the body of existing knowledge. Having said that, we must be aware of an important issue. That is the academic education provided by our schools is primarily aimed at nurturing the judicial mind. There is no assurance that schooling will necessarily contribute to the development of the creative mind.

Let me again take you back to the 1950s. In 1957, I developed a semiconducting device known as the Esaki tunnel diode. This diode could operate at very high speeds. But the true novelty of this diode is that it was the first quantum electron device. Namely, the wave nature of electrons was manifested for the first time in a semiconductor. This constituted my doctoral thesis, and I was awarded the Nobel Prize in Physics in 1973 for this achievement.

This new diode was highly acclaimed in the United States for its novelty. As a result, I was given the opportunity to go and work in America. One interesting thing about the tunnel diode is the way it was described by different people. Engineers said that I had invented it, while scientists said that I had discovered it. The Nobel Prize called it a discovery, as would be normal for the description of any scientific achievement. On the other hand, the tunnel diode was an invention from the viewpoint of patents and technologies. Inventions and discoveries both represent the fruits of our creative activities, but they clearly point to two different concepts. It is unusual to find something that can be labeled both an invention and a discovery. For instance, Antarctica was discovered, while the light bulb was invented. While I am certain that my own prejudice is partly responsible for the conclusion that I draw from this fact, I nevertheless believe that the tunnel diode stands at the intersection of science and technology.

DO-IT-YOURSELF QUANTUM MECHANICS: THE BIRTH OF THE SEMICONDUCTOR SUPERLATTICE

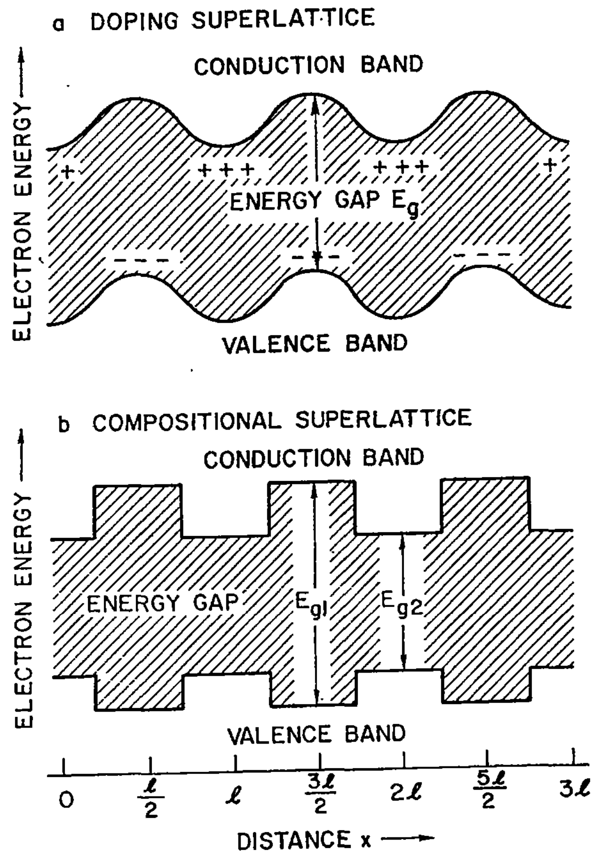

Figure 1: Spatial variations of the conduction and valence band edges in two types of superlattices: **a** doping, **b** compositional

In 1969, research on artificially structured materials was initiated with a proposal for an engineered semiconductor superlattice with a one-dimensional periodic potential by Esaki and Tsu (1969 and 1970). In anticipation of advancement in controlled epitaxy of ultra-thin layers, two types of superlattices were envisioned: Doping and compositional, as shown at the top and bottom of Fig. 1, respectively.

Before arriving at the superlattice concept, we were examining the feasibility of structural formation of potential barriers ad wells that were thin enough to exhibit resonant tunneling (Bohm, 1951). A resonant tunnel diode (Iogansen, 1963) (Tsu and Esaki, 1973) appeared to have more spectacular characteristics than the Esaki tunnel diode (Esaki, 1958): the first quantum electron device consisting of only a single tunnel barrier. It was thought that advanced technologies with semiconductors might be ready for demonstration of de Broglie electron waves. Resonant tunneling can be compared to the transmission of an electromagnetic wave through a Fabry-Perot resonator. The equivalent of a Fabry-Perot resonant cavity is formed by the semiconductor potential well sandwiched between the two potential barriers.

The idea of the superlattice occurred to us as a natural extension of double-, triple- and multiple-barrier structures: The superlattice consists of a series of potential wells coupled by resonant tunneling. An important parameter for the observation of quantum effects in the structure is the phase-coherent length, which approximates the electron mean free path. This depends on bulk as well as on the interface quality of crystals, and also on the temperatures and values of the effective mass. As schematically illustrated in Fig. 2, if characteristic dimensions such as superlattice periods or well widths are reduced to less than the phase-coherent length, the entire electron system will enter a mesoscopic quantum regime of low dimensionality, being in a scale between the macroscopic and the microscopic. Our proposal was indeed to explore quantum effects in the mesoscopic regime.

The introduction of the one-dimensional superlattice potential perturbs the band structure of the host materials, yielding a series of narrow subbands and forbidden gaps, which arise from the subdivision of the Brillouin zone into a series of minizones. Thus, the superlattice was expected to exhibit unprecedented electronic properties. At the inception of the superlattice idea, it was recognized that the long, tailored lattice period provided a unique opportunity to exploit electric field-induced effects. The electron dynamics in the superlattice direction was analyzed for conduction electrons in a narrow subband of a highly perturbed energy-wave vector relationship. The result led to the prediction of the occurrence of a negative differential resistance at a modestly high electric field, which could be a precursor of the Bloch oscillation. The superlattice, apparently, allows us to enter the regime of electric field-induced quantization: The formation of Stark ladders (James, 1949), (Wanniers, 1959 and 1960), for example, can be proved in a (one-dimensional) superlattice (Shokley, 1972), whereas, in natural (three-dimensional) crystals, the existence and real nature of these localized states in a high electric field have been controversial (Zak, 1968 and 1991), (Rabinovitch and Zak, 1971).

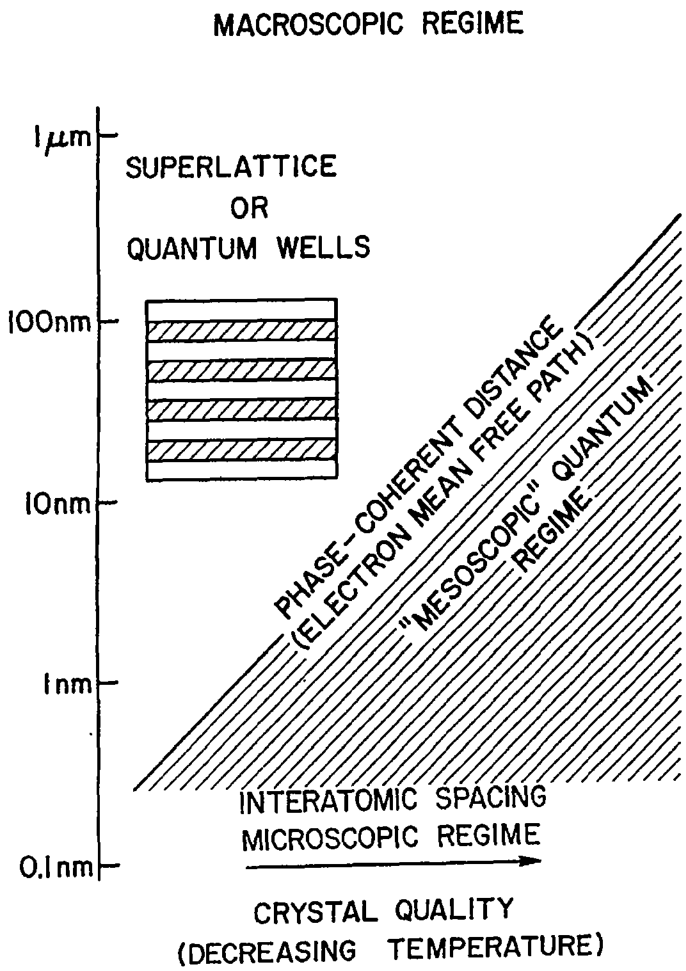

Figure 2: Schematic illustration of a 'mesoscopic' quantum regime (*hatched*) with a superlattice or quantum wells in the *inset*.

This was, perhaps, the first proposal, which advocated to engineer, with advanced thin-film growth techniques, a new semiconductor material designed by applying the principles of the quantum theory. The proposal was indeed made to the US Army Research Office (ARO), a funding agency, in 1969, having daringly stated, with little confidence in a successful outcome at the time, "the study of superlattices and observations of quantum mechanical effects on a new physical scale may provide a valuable area of investigation in the field of semiconductors".

Although this proposal was favorable received by ARO, the original version of the paper (Esaki and Tsu, 1969) was rejected for publication by Physical Review on the referee's unimaginative assertion that it was 'too speculative' and involved 'no new physics'. The shortened version published in *IBM J. Res. Develop.* (Esaki and Tsu, 1970), was selected as a Citation Classic by the Institute for Scientific Information (ISI) in July 1987. Our 1969 proposal was cited as one of the most innovative ideas at the ARO 40th Anniversary Symposium, Durham, North Carolina, 1991.

At any rate, with the proposal, we initiated such a formidable task as to make a '*gedanken*-experiment' a reality. In some circles the proposal was criticized as close to impossible. One of the objections was that a man-made structure with compositional variations in the order of several nanometers could not be thermodynamically stable because of interdiffusion effects. Fortunately, however, it turned out that interdiffusion was negligible at the temperatures involved.

In 1970, Esaki, Chang and Tsu (1970) studied a GaAs-$GaAs_{0.5}P_{0.5}$ superlattice with a period of 20 nm synthesizes with CVD (chemical vapor deposition) by Blakeslee and Aliotta (1970). Although transport measurements failed to reveal any predicted effect, the specimen probably constituted the first strained-layer superlattice having a relatively large lattice mismatch. Early efforts in our group to obtain epitaxial growth of $Ge_{1-x}Si_x$ and $Cd_{1-x}Hg_xTe$ superlattices were soon abandoned because of rather serious technological problems at that time. Instead we focused our research effort on compositional GaAs-$Ga_{1-x}AI_xAs$ superlattices growth with MBE (molecular beam epitaxy). In 1972, Esaki et al. (1972) found a negative resistance in such superlattices, which was, for the first time, interpreted in terms of superlattice effect.

Following the derivation of the voltage dependence of resonant tunnel currents (Esaki, 1958), Chang, Esaki and Tsu (1974) observed the current-voltage characteristics with a negative resistance. Subsequently, Esaki and Chang (1974) measured quantum transport properties in a superlattice with a narrow bandwidth, which exhibited an oscillatory behavior. Tsu et al. (1975) performed photocurrent measurements on superlattices subject to an electric field perpendicular to the plane layers with the use of a semitransparent Schottky contact, which revealed their miniband configurations.

Heteroepitaxy is of great interest for the growth of compositional superlattices. Innovations and improvements in epitaxial techniques such as MBE and MOCVD (metallo organic chemical vapor deposition) have made it possible to prepare high-quality heterostructures. Such structures possess predesigned potential profiles and impurity distributions with dimensional control close to interatomic spacing. This great precision has cleared access to the mesoscopic quantum regime (Esaki, 1986), (Esaki, 1991).

Since a one-dimensional potential can be introduced along with the growth direction, famous examples in the history of one-dimensional mathematical physics, including the above-mentioned resonant tunneling (Bohm, 1951), Kronig-Penney bands (1931), Tamm surface states (1932), Zener band-to-band tunneling (1934), and Stark ladders including Bloch oscillations (James, 1949), (Wannier, 1959 and 1960), (Shockley, 1972), all of which had remained more or less textbook exercises, could, for the first time, be practiced in a laboratory. Thus, do-it-yourself quantum mechanics is now possible, since its principles dictate the details of semiconductor structures (Esaki, 1992).

RETROSPECTING TO THE TWO DISCOVERIES

We have witnessed remarkable progress in semiconductor research of superlattices and quantum wells over the last two decades. Our original proposal (Esaki and Tsu, 1969) and pioneering experiments apparently triggered a wide spectrum of experimental and theoretical investigations on this subject. A variety of engineered structures exhibited extraordinary transport and optical properties, which may not even exist in any natural crystal. Thus, this new degree of freedom offered in semiconductor research through advanced material engineering has inspired many ingenious experiments, resulting in observations of not only predicted effects but also totally unknown phenomena have been found. As a measure of the growth of the field, Fig. 3 shows the number of papers related to the subject and the percentage of the total presented at the biennial International Conference on the Physics of Semiconductors. After 1972, when the first paper (Esaki *et al.*, 1972) came on the scene, the field went through a short period of incubation and then experienced a phenomenal expansion in the 1980s. It appears that nearly half of semiconductor physicists in the world are working in this area. Activity in this new frontier of semiconductor physics has in turn given immeasurable stimulus to device physics, provoking new ideas for applications. Thus, a new class of transport and opto-electronic devices has emerged. In this interdisciplinary research, there have been numerous beneficial cross-fertilizations. I hope this article provides some flavor of the excitement associated with the birth of the semiconductor superlattice.

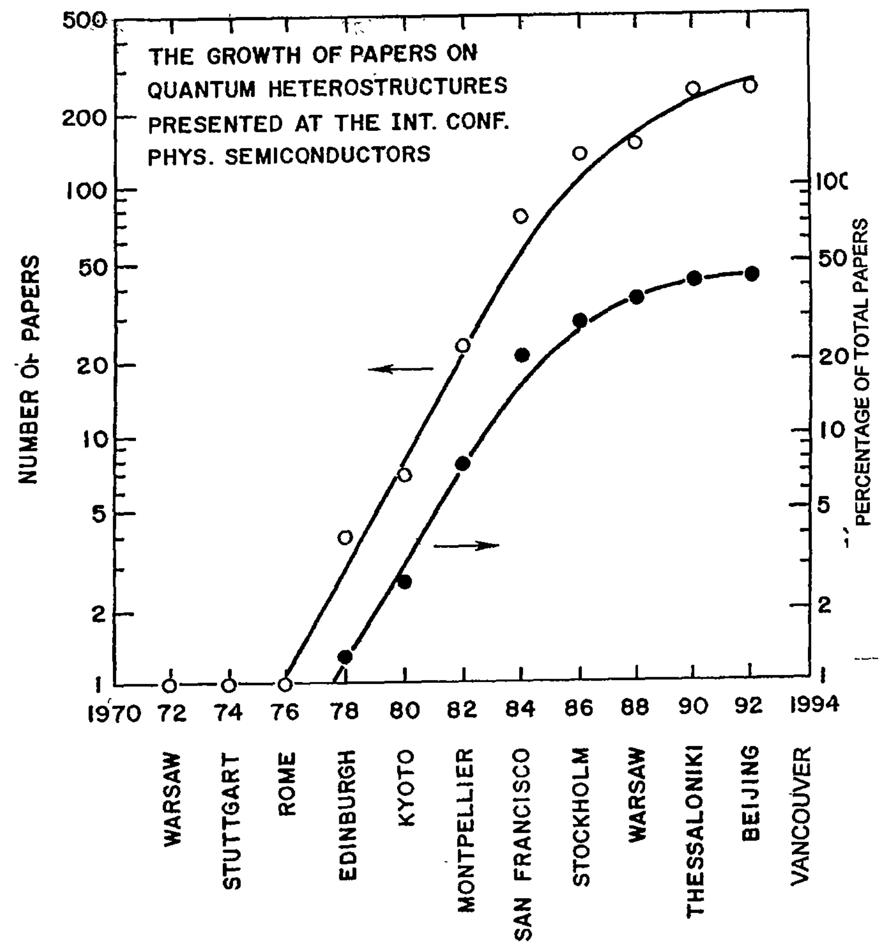

Figure 3: Growth in relevant papers in the biennial International Conference on the Physics of Semiconductors.

When I left IBM Research in New York and, after living in the United States for 32 years, I returned to Japan to take up my position as President of the University of Tsukuba, was not a move I had anticipated. The call came when a group of Tsukuba professors, who thought that the University needed 'new blood', nominated and elected me to be President. That was a minor revolution, which may upset some senior faculty members at the University. The circumstances of my election were indeed most unusual: I was the first president of any of Japan's 98 national universities to come from outside academia, and, what's more, I was working and living outside Japan. As you know, the country is rather famous for university inbreeding: the career path of choice is to obtain all degrees from the same university and then to stay there as a professor in the footsteps of the mentor. In view of this environment, my appointment was exceptional. In physics terms, it was almost a forbidden transition.

Today, I find myself doing my best to navigate through the academic woods.

The University of Tsukuba is located at the center of Tsukuba Science City, a planned community set up by the Japanese government three decades ago as a magnet for scientific and technical talents. To date more than 40 national research institutes have been drawn there - representing nearly half of the government's research facilities and 200 industrial laboratories. The High Energy Physics Laboratory (KEK), which you may know, is also at Tsukuba ten minutes drive from my office. In this rather unique environment, I am trying to increase collaboration and exchange with nearby national institutes and industrial research laboratories. Among other things, I plan to expand and strengthen Tsukuba's graduate education.

In closing, I would like to share with you a list of five 'don't'-s which anyone with an interest in realizing his or her creative potential should follow. Who knows, it may even help you win a Nobel Prize.

Rule number one: Don't allow yourself to be trapped by your past experiences. If you allow yourself to get caught up in social conventions or circumstances, you will not notice the opportunity for a dramatic leap forward when it presents itself. Looking back at the history of the Nobel Prize, you will notice that most of the laureates have received the Nobel Prize for work they had done during their thirties. In my case I was 32 years old when I developed the 'Esaki tunnel diode'. The point that I am trying to make is that younger people are able to look at things with a clear vision, one that is not clouded by social conventions and past history.

Rule number two: Don't allow yourself to become overly attached to any authority in your field - the great professor, perhaps. By becoming closely involved with the great professor, you risk losing sight of yourself and forfeiting the free spirit of youth.

Although the great professor may be awarded the Nobel Prize, it is unlikely that his subordinates will ever receive it.

Rule number three: Don't hold on to what you don't need. The information-oriented society facilitates easy access to an enormous amount of information. The brain can be compared to a personal computer with an energy consumption of about 25 watts. In terms of memory capacity or computing speed, the human brain has not really changed since ancient times. Therefore, we must constantly be inputting and deleting information, and we should save only the truly vital and relevant information. As the president of a university, I had the opportunity to meet many people and to exchange *meishi* (name card) with them. I try to discard the name cards as soon as possible, so that I always leave maximum memory space open. I'm kidding, of course.

Rule number four: Don't avoid confrontation. I myself became embroiled in some trouble with the company I was working for many years ago. At times, it is necessary to put yourself first and to defend your own position. My point is that fighting is sometimes unavoidable for the sake of self-defense.

Rule number five: Don't forget your spirit of childhood curiosity. It is the vital component for imagination.

Having listed five rules, let me say that they do not constitute the sufficient conditions for success. They are merely suggested guidelines. Good Luck!

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